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Primordial Nucleosynthesis and Finite Temperature QED

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Abstract

Abundances of light nuclei formed during primordial nucleosynthesis are theoretically well predicted by Standard Big Bang Model. These predictions have been compared with the latest data from WMAP with precisions higher than ever before. Therefore, an even more sharpened refinement in theoretical estimates is required through all possible approaches. We evaluate corrections to the change in helium abundance parameter during primordial nucleosynthesis using finite temperature corrections up to two loop level, for the first time. The values estimated are in measurable ranges of present and future observational probes.

Contents

I. INTRODUCTION

The universe was inconceivably hot during very initial fractions of a second that followed the Big Bang. As it evolved in time, it expanded and cooled extremely rapidly. With sufficient cooling the formation of elementary particles became possible. Big Bang cosmology [1], combined with the observational data from recent satellites and experimental data analysis from large-scale particle colliders, results in a confident extrapolation of history of universe back to an unprecedented early epoch after the Big Bang. Cosmic Background Explorer (COBE) and Wilkinson Microwave Anisotropy Probe (WMAP) [2] have been providing observational input for modifications to light element abundance parameters, at the time of Big Bang Nucleosynthesis (BBN) [3], due to their new and improved observational instruments. WMAP was specifically launched to confirm and reinforce the understanding of standard model of cosmology and precisely determine the cosmological parameters. It was stunningly successful during its seven years of operation providing precision up to five decimal places [4]. Latest observational missions, Planck and Herschel are providing data with unprecedented sensitivity, opening newer windows to study how the universe has evolved. It is fascinating to compare the theoretically predicted and observed values with more accuracy than was ever possible before. There has been a persistent effort to re-examine and refine the possibilities of improved theoretical input to these parameters and sharpen the predictions to match theory with measurements as precisely as possible.

BBN provides one of the earliest direct cosmological probes on properties of the universe when it was at a temperature scale of the order of a MeV ($\sim 10^{10}K$). The role of BBN in formation of primordial light elements has been extensively discussed in literature [5-42]. Helium-4 (^4He) yield is sensitive to the expansion rate of the early universe. Very early

universe contained highly energetic relativistic particles, i.e., photons, electrons, positrons and neutrinos. At such high energies the weak interactions given below played a major role [43-46] in regulating the relative number of protons and neutrons:

$$n \rightleftharpoons p + e^- + \overline{v}_e,$$

$$p + e^- \rightleftharpoons n + v_e,$$

$$n + e^+ \rightleftharpoons p + \overline{v}_e,$$

$$n + p \rightleftharpoons D + \gamma.$$

During the era of nucleosynthesis temperature was high enough for the mean energy per particle to be greater than the binding energy of D (2.2 MeV) thereby any D formed was immediately destroyed. Thus formation of ^4He was delayed until the universe became cool enough to form D (at $\sim T$ =0.1 MeV), when there was a sudden burst of formation of nuclei of light elements. The abundances of light elements got fixed and only changed as some of the radioactive products of BBN such as ^3He decayed. Theory of BBN provides a detailed description about production of $D,^3He$, ^4He, and ^7Li as well as precise quantitative predictions for their abundances. The theory predicts mass abundances of about 75% of ^1H, about 25% ^4He, about 0.01% of D, traces ($\sim 10^{-10}$) of Li and Be, and no other heavy elements. In standard picture of BBN, (SBBN), the universe is assumed to be homogeneous and all of the light element abundances depend on the amount of baryons relative to photons, $\eta_b = \frac{N_b}{N_\gamma}$. As the temperature of the universe dropped below 30 KeV, at a time around 20 minutes after the Big bang, η_b became small while the entropy increased. Coulomb barriers became significant enough at low temperature to eventually stop all nuclear reactions. Then until the first star formation there was no significant new elements production [47].

Changes brought about by cosmic expansion are combined with thermodynamics to calculate the fraction of protons and neutrons based on temperature. ^4He abundance is important because ^4He in the universe is much more than what could be explained by stellar nucleosynthesis. For ^4He, there is a good agreement of predictions from BBN with observations. Detailed calculations indicated that longer the thermal equilibrium sustained

between ν_e and $e^- - e^+ - \gamma$ the more neutrons survived to end up in more He production [48]. SBBN gives a measure for ^4He abundance $Y_p = 0.25$ which is taken equivalent to ^4He abundance on the basis that all the neutrons wind up into ^4He because of its stability. Luminosity of a star is analyzed to determine the abundance of a certain element in it [49]. The heavy element abundances Z contained by any star can give its opacity at a given density and temperature. In case of sun, the calculations identified ^4He abundance parameter Y to be 0.27 for a $Z = 0.02$ which was a very positive match with $Y = 0.27$ for a CMB temperature $3K$ [50, 51]. Interstellar observations give the He abundance to be $0.27 - 0.36$ which is also comparable with standard He abundance [52]. Primordial ^4He abundance $Y = 0.241 \pm\ 0.006$ leads to a very small baryon density parameter $\eta_{_{10}} < 3$ [15] (with $\eta_{_{10}} = 10^{10}\eta_b$) which is largely inconsistent with what was predicted by SBBN and D, i.e., $\eta_{_{10}} = 4 \pm 2$. ^4He abundance deduced from WMAP results, as a function of the baryonic density with Monte-Carlo calculation, gives $Y = 0.2476 \pm 0.0004$ [16]. More recently, data from WMAP showed that if the Big Bang creation model is correct, the value based on CMB prediction is $Y = 0.24819^{+0.00029}_{-0.00040} \pm 0.0006$ (syst.) [53]. Observations made in H_{II} regions which are low metallicity hydrogen clouds like dwarf galaxies, give the primordial ^4He abundance to be $Y = 0.249 \pm\ 0.009$ [54]. Similarly other observations give $Y = 0.247 \pm\ 0.001$ in zero metallicity regions [55] and $Y = 0.248 \pm\ 0.003$ observed in some other regions [56].

The perturbation in ^4He abundance during the era of primordial nucleosynthesis is related to mass shift arising from radiative corrections to particles propagating in the early universe [43-46]. The temperature range particularly of relevance in primordial nucleosynthesis of light elements is the range where finite temperature Quantum Electrodynamics (QED) interactions are valid. At these temperatures virtual electron-positron pairs couple to photons in loops, and vice versa, affecting particle dispersion. Abundances of light elements formed in the early universe are influenced by finite temperature effects. One loop corrections to QED processes have been calculated in detail not only at finite temperature but also by including densities for various physical environments [57-67]. The density effects in early universe during the era of BBN were, however, so small in comparison with temperature that they can be ignored. We prefer using real time formalism because the temperature corrections with this formalism are obtained as separate terms additive to the zero temperature part. At finite temperature, the corrections are usually calculated for limiting cases of temperature $T \ll m$ and $T > m$, where m is the electron mass. These were

re-examined in a general form so that the range of threshold temperatures ($T \sim m$) for the creation of electron positron pairs are also included [63]. The ranges of temperature $T \ll m$ and $T > m$ can be retrieved as limiting cases. Higher order modifications to the electron self mass are worth estimating for even finer corrections.

II. SELF ENERGY OF ELECTRON AT FINITE TEMPERATURE

Quantum Field Theory assumes that particles are analogous to excitations of a harmonically oscillating field permeating space-time. Modern interpretation of vacuum is an absence of particles, which is not devoid of energy and fields. Vacuum is treated as a bath of virtual particles which can mediate interactions between real particles. Particle propagation in vacuum can be taken to be the propagation with interactions switched off. On the other hand, the particles propagating through a medium involve several kinds of interactions between real and virtual particles in the background. Therefore properties of a system with background medium are somewhat different from a system in which all the particles propagate freely. In finite temperature environments, relevant in QED, electrons and photons propagate in statistical background at energies around thresholds for the production of electron-positron pairs. Therefore, temperature effects that arise due to continuous particle exchanges during the physical interactions in a heat bath containing hot particles and antiparticles need to be appropriately taken into consideration.

Calculations involved in finite-temperature field theory are similar to those in perturbative quantum field theory at $T = 0$. The interactions taking place when photons propagate through a system in the presence of fermions in the background, or vice versa, contribute to perturbative corrections in dynamics describing the system. The statistical effects of particles propagating in a heat bath of photons, electrons and positrons at finite temperature enter the theory through Fermi-Dirac and Bose-Einstein distribution functions. These interactions with the background heat bath are incorporated by modifying the particle propagators. Using the finite temperature formulations, scattering amplitudes and loop corrections are calculated. From poles of the propagators, modified dispersion relations are obtained [60].

Figure 1. One loop
electron self energy

Self energies of particles acquire temperature corrections in a heat bath due to energy momentum exchanges with real particles. Thermal mass is radiatively generated in such particle interactions and serves as a kinematical cut-off, in production rate of particles from the heat bath. Electrons and photons acquire dynamically generated mass due to plasma screening through the self energy corrections at finite temperature. This leads to modification in masses, coupling etc., of interacting particles at finite temperature and electromagnetic properties of the medium in which they propagate are influenced. Physical mass of electron at one loop in figure 1 was obtained in ref. [60] for $T \ll m$ and $T > m$. Using the corrections to electron self energy, first order in α corrections to primordial parameters have been determined in ref. [58] for these limits of temperature. In particular from the point of view of light elements abundances at the time of primordial nucleosynthesis, self energy corrections to electron propagators have been of significance even at $T \sim m$ [67]. Corrections to electron and photon self energy have been calculated at the two loop level [68-72], in real time formalism.

III. MODIFIED ELECTRON MASS AT FINITE TEMPERATURE

During primordial nucleosynthesis the relative changes in Helium abundance parameter, neutron decay rate, energy density, etc. have been shown to depend on relative shift in electron mass [43-46]. The relative shift in electron mass is calculated at order α^2 by one particle reducible and one particle irreducible self energy diagrams with two loops in figure 2 and figure 3 respectively.

Figure 2. Two loop one particle reducible electron self energy

Figure 3. Two loop one particle irreducible electron self energy

This shift in electron mass up to second order in α was calculated in detail [71] in a general form in which $T \sim m$ was also inclusively represented. The results for $T \ll m$ and $T > m$ were retrievable as limiting cases. The mass shift is calculated using the expression

$$\Sigma(p) = A(p)E\gamma_0 - B(p)\vec{p}.\vec{\gamma} - C(p),$$

where $A(p)$, $B(p)$, and $C(p)$ are the relevant coefficients [60]. Taking the inverse of the propagator with momentum and mass term separated as

$$S^{-1}(p) = (1 - A)E\gamma^o - (1 - B)p.\gamma - (m - C),$$

the physical mass of an electron $m_{phy} = m + \delta m^{(1)} + \delta m^{(2)}$, was deduced by locating the pole of propagator $\frac{i(\not{p}+m)}{p^2 - m^2 + i\varepsilon}$. Here $\delta m^{(1)}$ and $\delta m^{(2)}$ is shift in electron mass due to temperature effects at one and two loop level respectively. One particle reducible two loop corrections in figure 2 were presented in ref. [71] to obtain an expression for $\frac{\delta m}{m}$ but they were not studied in the context of applications to primordial nucleosynthesis. The expression for self energy

obtained was:

$$\left(\frac{\delta m}{m}\right)^n \simeq \left(\frac{\alpha\pi T^2}{2m^2}\right)^n, \tag{1}$$

where n represents the number of loops under consideration. Thus for one particle reducible diagrams, on iteration of one loop result obtained in ref. [63], the relative change in electron mass becomes:

$$\left(\frac{\delta m}{m}\right)^2 \simeq \frac{\alpha^2\pi^2 T^4}{4m^4}. \tag{2}$$

In case of one particle irreducible diagram for two loops in figure 3, the leading term [71] is:

$$\frac{\delta m^{(2)}}{m} = -\frac{16\alpha^2}{\pi^2}\varsigma(3)\left(\frac{T}{m}\right)^3\left(\frac{E}{m}\right)^2. \tag{3}$$

Using these expression for relative change in electron mass in eq. (2) and eq. (3), one can determine the temperature effect on the primordial ^4He abundance parameter ΔY at the two loop level.

IV. SUMMARY AND RESULTS

Formation of chemical elements is essential for understanding the evolution of universe. ^4He formation has been particularly paramount for study of cosmology and chemical evolution of galaxies. There are theoretical as well as observational predictions for ^4He abundance parameter. The existence of finite temperature background at the time of synthesis of light nuclei makes it relevant to include its corrections while determining the variation in primordial ^4He abundance. Here we calculate the two loop corrections to Helium abundance parameter related to electron mass shift [44-46, 57-60], $\frac{\delta m}{m}$ arising from radiative corrections, which are given by

$$\Delta Y = -0.2\frac{\Delta\lambda}{\lambda}, \tag{4}$$

where $\frac{\Delta\lambda}{\lambda}$ is relative change in neutron decay rate. This ratio is

$$\frac{\Delta\lambda}{\lambda} = -0.2\left(\frac{m}{T}\right)^2\frac{\delta m}{m}, \tag{5}$$

with m as the mass of the propagating particle, T is the temperature of background heat bath. In early universe temperature effects prevailed over density effects with $\mu/T \leqslant 10^{-9}$,

where μ is the chemical potential of the particles such as electrons, neutrinos and their anti particles present in the background. Equation (5) can be substituted in eq. (4) for ΔY to get

$$\Delta Y = 0.04 \left(\frac{m}{T}\right)^2 \frac{\delta m}{m}. \tag{6}$$

One loop corrections estimated in ref. [59] give $\Delta Y = 0.4\times 10^{-3}$ at $T \sim m$ which falls to 0.3×10^{-3} at $T \sim m/3$. For two loop corrections to electron self energy given in figures 2 and 3, the values of $\frac{\delta m}{m}$ and ΔY are calculated for the range of temperature $0.1 \times 10^{10}K \leqslant T \leqslant 1.4 \times 10^{10}K$. From eqs. (2) and (3) for one particle reducible and one particle irreducible diagrams at two loop level in figs. (2) and (3) respectively, $\frac{\delta m}{m}$ is estimated individually and also by combining results from both the cases. These values are presented in table 1. Further, ΔY from both the possibilities is estimated separately along with the combined effect in table1.

T (MeV)	$\frac{\delta m^{(reducible)}}{m}$	$\frac{\delta m^{(irreducible)}}{m}$	$\frac{\delta m^{(total)}}{m}$	$\Delta Y^{(reducible)}$	$\Delta Y^{(irreducible)}$	$\Delta Y^{(total)}$
0.1	1.93×10^{-7}	-2.97×10^{-7}	-1.04×10^{-7}	2.02×10^{-7}	-3.11×10^{-8}	1.70×10^{-7}
0.2	3.09×10^{-6}	-2.4×10^{-5}	-2.10×10^{-5}	8.06×10^{-7}	-2.49×10^{-7}	5.57×10^{-7}
0.4	4.94×10^{-5}	-1.90×10^{-4}	-1.40×10^{-4}	3.22×10^{-6}	-1.99×10^{-6}	1.23×10^{-6}
0.6	2.50×10^{-4}	-6.50×10^{-4}	-4.00×10^{-4}	7.26×10^{-6}	-6.72×10^{-6}	5.40×10^{-7}
0.8	7.90×10^{-4}	-15.4×10^{-4}	-7.50×10^{-4}	1.29×10^{-5}	-1.59×10^{-5}	-3.00×10^{-6}
1.0	1.93×10^{-3}	-3.01×10^{-3}	-1.08×10^{-3}	2.02×10^{-5}	-3.11×10^{-5}	-1.09×10^{-5}
1.2	4.00×10^{-3}	-5.20×10^{-3}	-1.20×10^{-3}	2.90×10^{-5}	-5.37×10^{-5}	-2.47×10^{-5}
1.4	7.41×10^{-3}	-8.27×10^{-3}	-0.86×10^{-3}	3.95×10^{-5}	-8.53×10^{-5}	-4.58×10^{-5}

Table 1. The values of relative shift in electron mass $\frac{\delta m}{m}$ and ^4He abundance parameter ΔY calculated for one particle reducible and one particle irreducible self energy and

their combined affect for temperatures in the range $0.1 \times 10^{10} K \leqslant T \leqslant 1.4 \times 10^{10} K$.

Figure 4. ΔY vs T for one particle reducible (dashed line), one particle irreducible (dashed-dotted line), and total corrections (solid line)

Two loop corrections to $\frac{\delta m}{m}$ for one particle reducible contribution in eq. (2), one particle irreducible contribution in eq. (3), and overall corrections from the two possibilities are used to plot ΔY versus T for the relevant range of temperature $0.1 \times 10^{10} K \leqslant T \leqslant 1.0 \times 10^{10} K$ in figure 4, for a comparison. At temperature $T \sim m$, one gets $\Delta Y = -0.388 \times 10^{-5}$ from one particle irreducible diagram whereas $\Delta Y = 0.504 \times 10^{-5}$ from one particle reducible diagram. The overall contribution at $T \sim m$ is $\Delta Y = 0.116 \times 10^{-5}$ which decreases as the temperature increases. As mentioned earlier [72], at energies of the order of 1 MeV, $\Delta Y = -0.311 \times 10^{-5}$ from one particle irreducible diagram whereas $\Delta Y = -0.109 \times 10^{-5}$ from one particle reducible diagram with an overall contribution $\Delta Y = 0.115 \times 10^{-5}$. Figure 4 and table 1 show that although the two loop corrections at finite temperature are small but they are not completely negligible in comparison with values obtained through observational probes.

The finite temperature corrections are not only interesting since they give non-negligible correction but they can be a source of further modification in theoretically predicted values. QED corrections obtained by Dicus *et al.* [43] with one loop corrections are already included

in the BBN codes [30]. WMAP has been providing modifications to light element abundance parameters up to five decimal places. The recent observational probes such as Planck, Herschel and James Webb Space Telescope are expected to provide further fine tuning in precision values of these parameters. Modifications to electron mass at finite temperature beyond second order in α may be interesting for further refinement in these corrections. Second order corrections to weak processes will be interesting and useful for estimating modifications to ΔY due to weak interactions. This will be aimed for in our future work.

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Figure captions

Figure 1. One loop electron self energy

Figure 2. Two loop one particle reducible electron self energy

Figure 3. Two loop one particle irreducible electron self energy

Figure 4. ΔY vs T for one particle reducible (dashed curve), one particle irreducible (dashed-dotted curve), and total corrections (solid curve).

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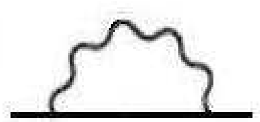

Figure 1. One loop electron self energy

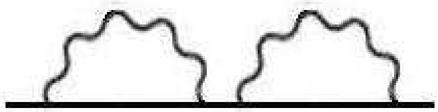

Figure 2. Two loop one particle reducible electron self energy

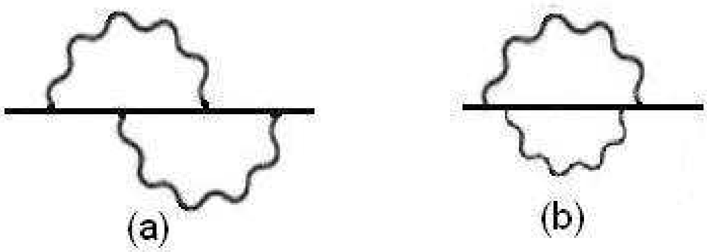

Figure 3. Two loop one particle irreducible electron self energy

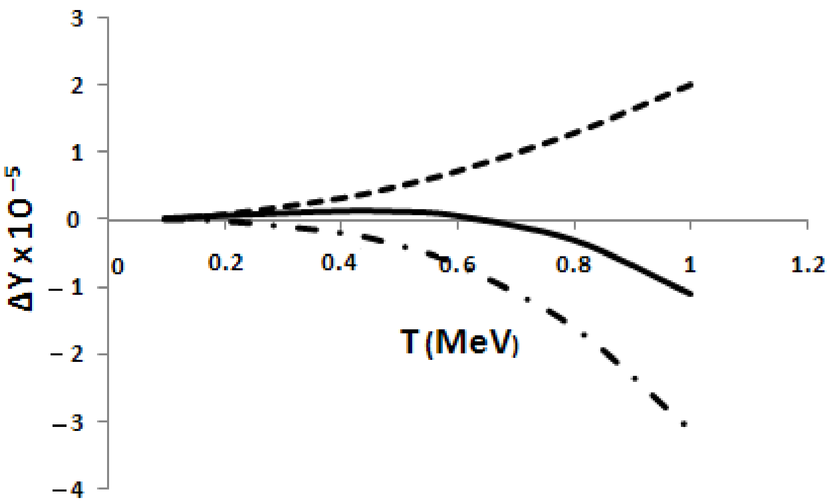

Figure 4. Y vs T for one particle reducible (dashed line), one particle irreducible (dashed-dotted line), and total corrections (solid line)